Piled rafts with hollow auger piles for building foundations in sand deposits in northeastern Brazil

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ABSTRACT
Usually, geotechnical projects predict load transfer to the ground by means of shallow or deep foundations. Conventional design approach does not provide the combination of these two types of foundation. The piled raft philosophy allows the association of both the soil elements, raft and piles, in order to obtain technical and economic advantages over the conventional design. The city of Joao Pessoa, in northeastern Brazil, has developed foundation practices with hollow auger piles in piled raft design. The coastal area of the city presents superficial soil layers with favorable conditions for using such technique. This paper shows results of instrumented load tests performed over foundations systems of hollow auger piles and piled raft. The case of a raft and a piled raft is evaluated with analysis of the load x settlement curve through extrapolation criteria. Instrumentation analysis describes the load distribution process between raft and pile during charging. Results indicate that the load is first absorbed by the raft and that soil-raft contact contributes significantly to the system's bearing capacity.

RESUMEM
Generalmente, los proyectos geotécnicos predicen la transferencia de carga al suelo por medio de cimentaciones poco profundas o profundas. El enfoque de diseño convencional no ofrece la combinación de estos dos tipos de elementos estructurales. La filosofía de cimentación mixta losa-pilotes permite la asociación de ambos elementos del suelo, losa y pilotes, con el fin de obtener ventajas económicas y técnicas sobre el diseño convencional. La ciudad de Joao Pessoa, en el nordeste de Brasil, ha desarrollado prácticas de fundación con pilotes hollow auger en el diseño de losa pilotada. La zona costera de la ciudad tiene capas superficiales del suelo con las condiciones favorables para el uso de esta técnica. Este trabajo presenta los resultados de las pruebas de carga instrumentadas realizadas en los sistemas de grupos de pilotes hollow auger y losas pilotadas. El caso de una losa de cimentación y de losa pilotada se evalúa con el análisis de la curva de carga x asentamiento a través de criterios de extrapolación. El análisis de instrumentación describe el proceso de distribución de carga entre la losa y pilote durante la carga. Los resultados indican que la carga es primero absorbida por la losa y que en contacto con el suelo, esta contribuye significativamente a la capacidad de carga del sistema.

1 INTRODUCTION

Conventional foundation projects provide the load transfer to the ground by considering options of deep or shallow foundation. Traditionally distinct elements are not involved in the same foundation.

The piled raft is an alternative approach to conventional design foundation. The new concept combines both the shallow and deep foundations in a single element, and the advantages of each party in a new set. More details about it are found in Randolh (1994), Poulos (2001) and Mandolini (2003).

The city of Joao Pessoa, in northeastern Brazil, has developed foundation practices with hollow auger piles in piled raft design. The coastal area of the city has superficial soil layers with favorable conditions for the use of this technique. It is represented by Quaternary sediments and consists of sand with silt and clay. The standard penetration resistance (N-value) presents growing values up to 5.0 m depth reaching values between 25 and 40. Such conditions allow load transfer to the ground to be shared among the raft and piles, which have maximum length of 5.0 m.

The hollow auger is a steam auger-shaped tube, fitted with a propeller cutting along its entire length. Works as a cutting tool into the soil and as a coating recoverable. Its shape keeps the hole stability and prevent water from entering inside.

Although hollow auger piles occupy an important niche within local foundations practice, design calculations still rely heavily on empirical knowledge and information of the hollow auger piles are not disclosed by the executing companies.

This article is part of doctorated research developed by the Federal University of Pernambuco and studies the behavior of hollow auger pile foundations arranged in pile groups and piled raft. Static load tests were performed in an experimental field of foundations located in the coastal area of João Pessoa.

Instrumentation was used with load cells and strain gages, positioned along shafts and pile tips. Analysis show the load distribution between piles (pile group), between piles and raft (piled raft), and along shafts and pile tips.

2 AREA OF STUDY

Experiments in the field were carried out on the coast of the city of João Pessoa in Northeastern Brazil. Following Conciani et al. (1999), the region presents subsoil composed of marine sediments from the Holocene (quaternary age). Those sediments are composed of sands with silt and clay superposed in layers of different degrees of compactness. This stratification may have arisen from the rise and fall of ocean levels through out the ages. Figure 1 shows a local SPT.

The region is part of the coastal marine deposits and is situated within the field of geomorphology in Coastal Lowlands (Figure 2).

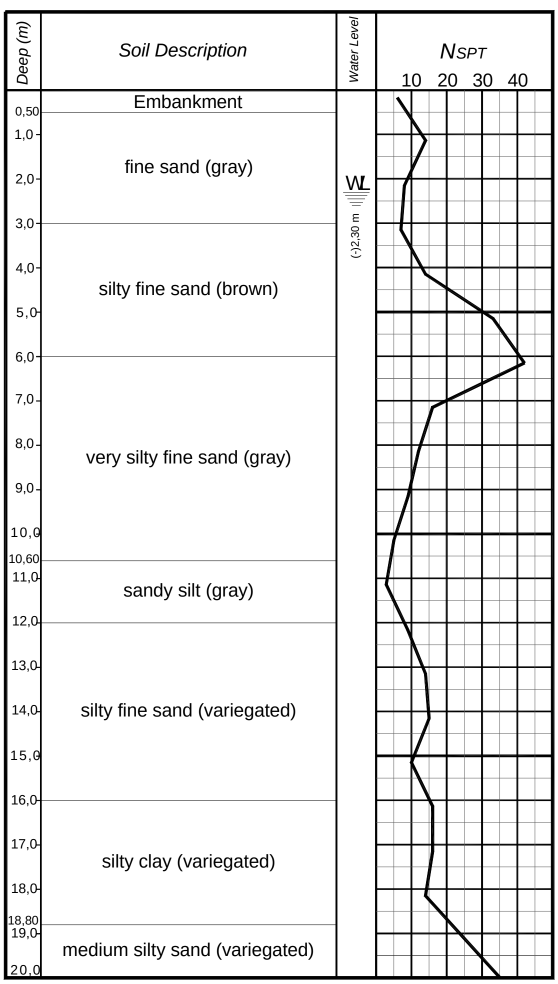

Figure 1 Standard Penetration Test

Figure 2 Coast of João Pessoa

Fourteen hollow auger piles with a diameter of 0.30 m and 5.0 m in length were performed, with spacing between piles of 1.05 m (3.5d).

The piles were divided into two types of foundation systems: pile group and piled raft. In each type of foundation, models were created with one, two and four piles (Table 1). Six load tests were carried in both types of foundation and one load test in a single raft.

Table 1. Types of foundation

Pile Groups	Piled Rafts
1 pile	1 pile
2 piles	2 piles
4 piles	4 piles

The raft support characterizes the type of foundation. In the group of piles, the raft rests only on the piles (Figure 3a). In the piled raft, it rests on the piles and soil (Figure 3b).

The load distribution between piles and between raft and piles was measured with load cells mounted in the laboratory. Strain gages were installed on a pile of each type of foundation, positioned at the top and the pile tip. The sensors, mounted in complete Wheatstone bridge circuits, measure the peak load and the lateral friction of the pile.

The scheme of load measurement (cells and strain gages) in the experimental load tests is shown in Figure 4.

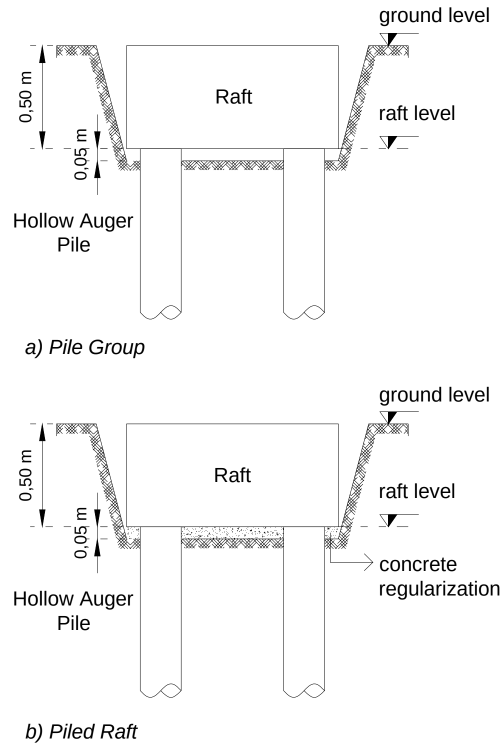

Figure 3 Types of foundation: (a) pile groups; (b) piled raft

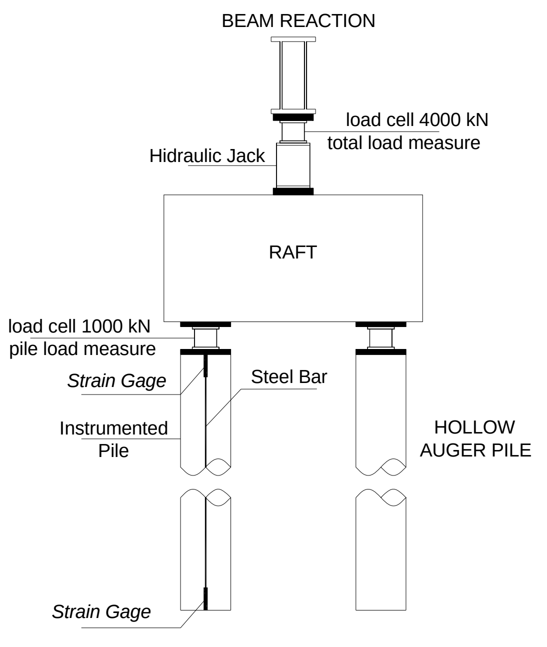

Figure 4. Instrumentation scheme

Loads in the group of piles were measured by the cells of 1000 kN capacity. The load on the raft is determined by subtracting from the value of the total load (cell of 4000 kN capacity) the sum of the load of cells (1000 kN capacity).

This paper will present the case of foundations in two pile groups and piled raft (two piles). It will also be featured a case of isolated pile instrumented with strain gages. For further information see Soares 2011.

3 RESULTS

3.1 Load tests

The Figure 5 and Figure 6 show the load settlement curves of the two piles group and raft with two piles.

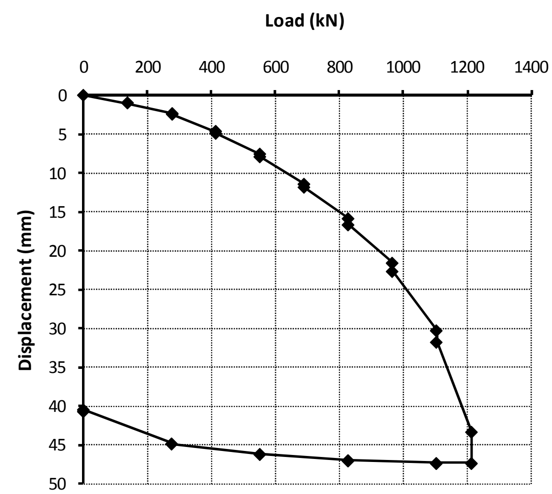

Figure 5 Load x settlement curve for two piles groups

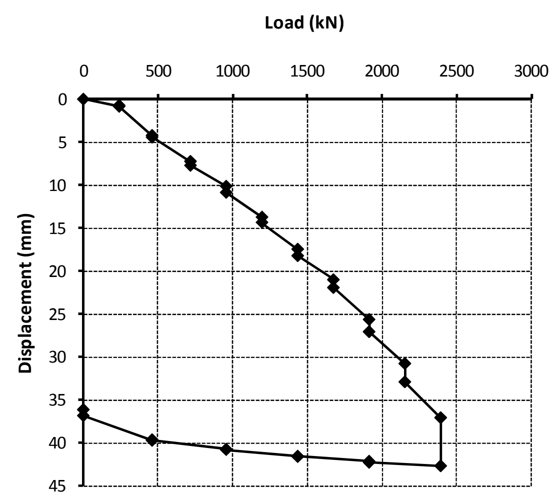

Figure 6 Load x settlement curve for piled raft with two piles

Table 2 shows the data values of maximum load and settlement reached during the load test.

Table 2. Maximum values of load and settlement reached.

Test	Load (kN)	Displacement (mm)
2 piles group	1214	47.35
Raft pile (2 piles)	2392	42.70

3.2 Instrumentation

The load distribution between the raft (Q_R) and pile group (Q_{PG}) measured by load cells during loading test is shown in Figure 7.

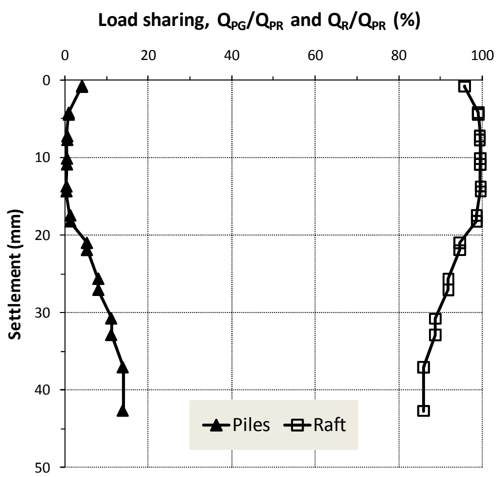

Figure 7 Measurement of load sharing between piles and raft

Load transfer to soil by skin friction and the pile tip instrumented with strain gages is shown in Figure 8.

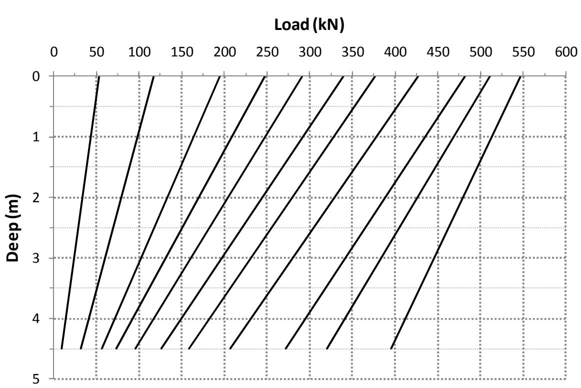

Figure 8 Load transfer to soil by skin friction and the pile tip

It was determined the loads on the sections of the pile (top and tip) through the secant modulus at the suggestion of Fellenius (2001).

4 ANALYSIS

4.1 Load x settlement curve

To evaluate the foundation bearing capacity, from the load x settlement curves, it was used the extrapolation methods by Van der Veen (1953) and the method of Décourt (1996), based on the concept of stiffness to characterize the physical rupture. It was also used a limit settlement criterion (ρ_{lim}), adopted as 40 mm, as suggested by Skempton & MacDonald (1956) for shallow foundation on sand, to evaluate the allowable load on foundations.

Extrapolations of the load settlement curve of the tests and estimates of load corresponding to the limit settlement are shown in Figure 9 and Figure 10.

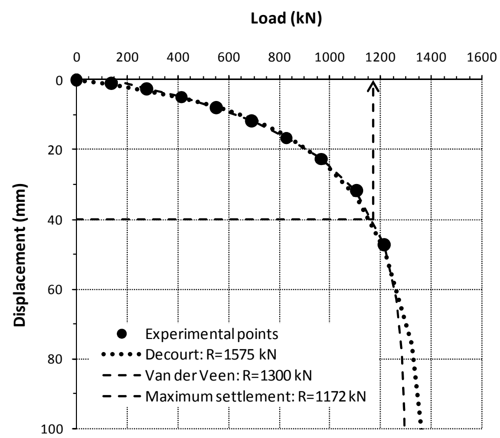

Figure 9 Extrapolating curves for the groups of two piles

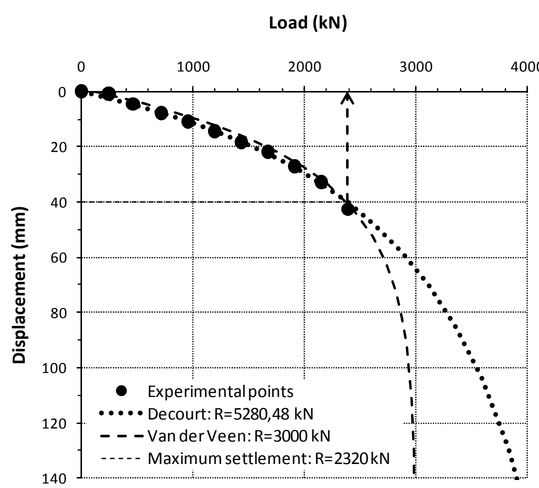

Figure 10 Extrapolating curves for 2-piled raft

The bearing capacity of foundations (R), obtained by extrapolation methods (Van der Veen and Décourt), and the loads that cause the limit settlement ($P_{\rho max}$), are shown in Table 3.

Table 3. Bearing capacity of foundation through the extrapolation criteria and limit settlement

Test	Van der Veen (kN)	Décourt ・方・	Limit Settlement (kN)
2 piles group	1300	1575	1172
Raft pile (2 piles)	3000	5280.5	2320

The allowable load of foundations (P_{al}) is calculated with a 2.0 safety factor applied to extrapolated loads, and a 1.5 safety factor applied to loads ($P\rho_{lim}$) which produce the limit settlement of 40 mm.

Allowable loads (P_{al}) of the tests, according to the methods of prediction are shown in Table 4.

Table 4. Allowable load of the tests.

Test	Van der Veen (kN)	Décourt (kN)	Limit Settlement (kN)
2 piles group	650	787.5	781.3
Raft pile (2 piles)	1500	2640.2	1546.7

The extrapolation methods (Van der Veen and Décourt) yielded good fits to the load x settlement curves.

For the group of piles, the methods of analysis predict values of allowable load with the same order of magnitude.

For the piled raft the criterion of Van der Veen and the criterion of limit settlement show very close values to working load.

The allowable load of piled raft according to the method of Décourt does not follow the deformation limit criteria.

Its value (48.8 mm) exceeds the limit of 25 mm, recommended by Terzaghi & Peck (1967), as allowable settlement (ρ_{ad}), for shallow foundation on sand.

For purposes of this study the criterion of limit settlement (ρ_{lim}) of 40 mm was chosen as bearing capacity of foundations.

4.2 Increase of bearing capacity of piled raft (ζ_{PR})

The coefficient ζ_{PR} (Mandolini; Russo and Viggiani, 2005) indicates the increase of bearing capacity of piled raft due the raft contact with the soil. It is expressed by:

$$\zeta_{PR} = \frac{Q_{PR}}{Q_P} \qquad [1]$$

where, Q_{PR} is the piled raft load and Q_P is the pile group load.

The increase in bearing capacity of foundation (ζ_{PR}) is shown in Figure 11 and Table 5.

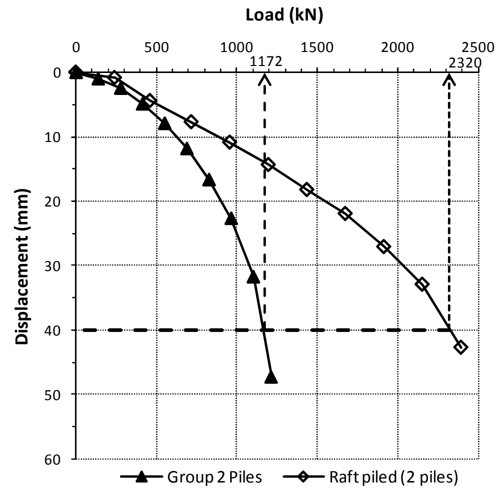

Figure 11 bearing capacity of foundations

Table 5. Increase of bearing capacity of piled raft (ζ_{PR})

Test	Bearing Capacity	ζ_{PR}
2 piles group	1172 kN	1.98
Raft pile (2 piles)	2320 kN	

The raft contact with the soil has increased by approximately twice the load capacity of the foundation.

The results for one-piled group and another with four piles (see SOARES 2011) show that ζ_{PR} increases according to the reduction in the number of piles, as reported by Cooke (1986).

4.3 Instrumentation

The instrumentation with load cells showed that the raft absorbs the initial loads and the piles were mobilized after the settlements of about 20 mm.

The distribution of load between the piles and the raft (Figure 7) varied during the stages of loading and reached the following final values: Q_{PG} / Q_{PR} = 14%; Q_R / Q_{PR} = 86%.

The large portion of the raft load (86 %) is due the good resistance of the soil near the surface.

The analysis of load transfer at the single pile shows that the percentage of load absorbed by the tip increases from the middle- stage of loading. Its value ranges from 30% to applied load of 250 kN, and reaches 72% for the applied load of 550 kN.

5 CONCLUSIONS

The result of this study shows the benefits of raft-soil contact.

The extrapolation methods adopted (Van der Veen and Décourt) yielded good fits to load x settlement curves of foundations.

Comparing the different methods used (Van der Veen, Décourt and limit settlement), the values of the allowable loads for group piles are close.

For the piled raft, those values are close when obtained from the methods of Van der Veen and limit settlement. The criterion of Décourt provides the highest values of allowable loads. Its correspondent settlement (48.8 mm) exceeds the limit of 25 mm, recommended by Terzaghi & Peck (1967), as allowable settlement (ρ_{ad}), and the limit of 40 mm for limit settlement (ρ_{lim}), suggested by Skempton & MacDonald (1956) for shallow foundations in sand.

The raft contact with the soil increased at almost twice as much the bearing capacity of the foundation when compared to the pile group.

The instrumentation with load cells allowed to quantify the values of load distributed between the raft and piles. The raft sits on a soil layer of high resistance and absorbed most of the load (86%).

The analysis of load transfer in the instrumented pile shows that the percentage of peak load increases with the stages of loading. In intermediate stages, the tip absorbs 30% of the applied load and at the last stage the load value reaches 72%.

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